Critical Care, Third Edition, edited by Joseph M. Civetta, Robert W. Taylor, and Robert R. Kirby.
Lippincott-Raven Publishers, Philadelphia, PA © 1997.

CHAPTER 56

Invasive Pressure Monitoring

Reed M. Gardner

Invasive pressure monitoring, now routinely performed at the patient's bedside, incorporates more advanced technology than was formerly used in heart cardiac catheterization laboratories. The monitoring enables the clinician to have a better understanding of the relationship between the pressure and blood flow in the patient's cardiovascular system. However, every measuring system can produce false information. Constant vigilance and understanding of such systems is the best prescription for ensuring acquisition of high-quality pressure monitoring information.

Arterial blood pressure can be measured by both invasive and noninvasive means. However, central venous pressure, pulmonary artery (PA), and pulmonary artery occlusion pressure (PAOP) currently can be measured only by invasive means.

Continuous and accurate assessment of blood pressures can only be made invasively. Having continuous pressure data available permits timely detection of dangerous hemodynamic events and provides the information necessary to initiate and titrate patient therapy. Nevertheless, invasive pressure monitoring provides valuable information *only* when correct techniques are used to obtain accurate data.

This chapter covers the technical aspects of invasive monitoring. Details about catheter insertion techniques are presented in Chapter 57. Complications associated with pressure physiologic measurements, clinical understanding, and managing patient-related problems also are discussed in other chapters of this book.

EQUIPMENT

The components used for invasive pressure monitoring are shown in Figure 56-1.[1,2] This diagram illustrates an arterial site, but a similar setup is appropriate for PA pressure measurement. The components known as the "plumbing system" (see Fig. 56-1, points 1 through 6) must be kept sterile because they come in direct contact with the patient's blood. Usually, these components are disposable. The other components (see Fig. 56-1, points 7 through 10) in the system are used for processing and displaying pressure waveforms and for obtaining derived hemodynamic parameters.

CATHETER

Arterial and PA catheters provide access to the patient's blood vessels for pressure monitoring and provide a site for withdrawing blood samples for blood gas analysis and other tests.

STOPCOCK NO. 1

Stopcock no. 1 is used as a site for withdrawing blood for analysis. When filling the plumbing system with fluid, precautions must be taken to be sure that all central switching cavities of the stopcock are fluid filled. All entrapped air bubbles must be removed. Stopcocks are particularly vulnerable sources of patient contamination. Therefore, stopcocks should be handled with extreme care; ports not in active use should be covered with sterile caps, and the open ports should never be touched.

PRESSURE TUBING

The catheter and stopcock are normally attached to the continuous flush device and pressure transducer by nonelastic pressure tubing. To optimize the dynamic response of the plumbing system, avoid long lengths of tubing.

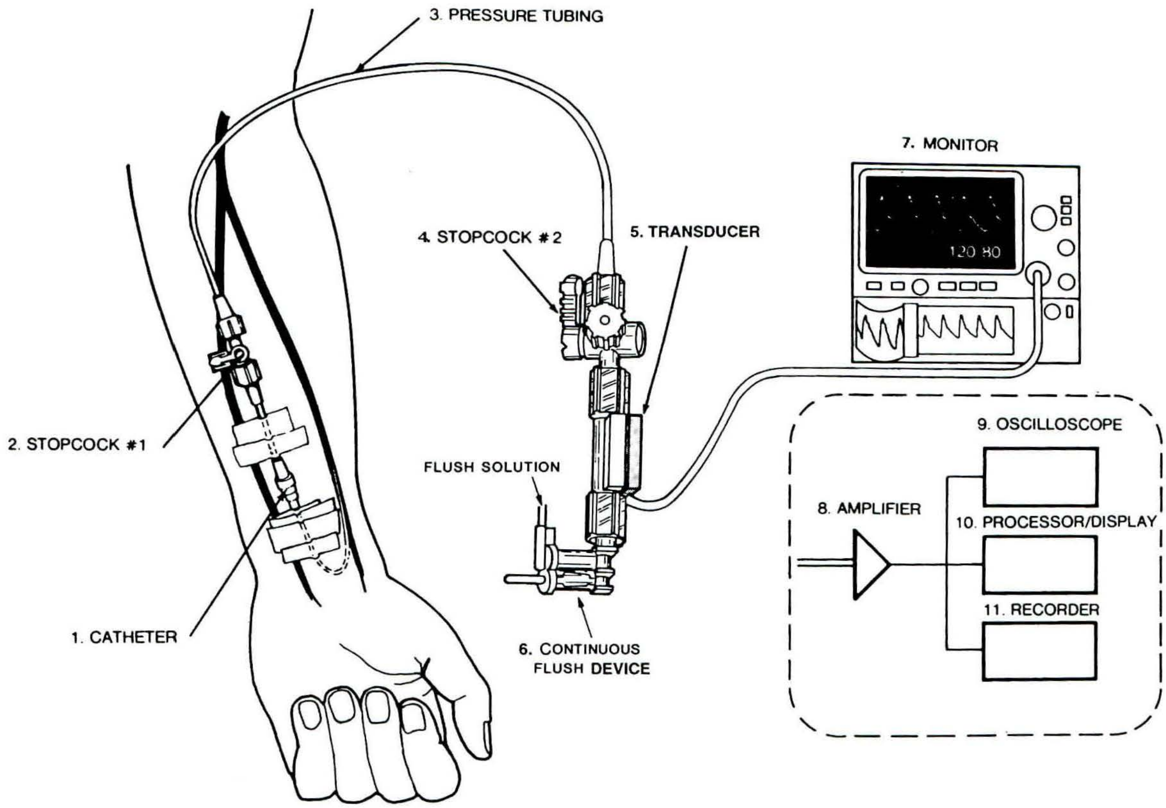

FIGURE 56-1. Components used to monitor blood pressure directly are nearly the same, independent of whether the catheter is in an artery (radial, brachial, or femoral) or in the pulmonary artery. The size of the transducer and plumbing components were enlarged for the illustration. (Adapted from Gardner RM, Hollingsworth KW: Optimizing ECG and pressure monitoring. *Crit Care Med* 1986;14:651.)

STOPCOCK NO. 2

If the transducer is patient mounted when measuring arterial pressures, stopcock no. 2 may not be necessary.

CONTINUOUS FLUSH DEVICE

The continuous flush device is used to fill the pressure monitoring system with fluid and helps prevent blood from clotting in the catheter by continuously flushing fluid through the system at a rate of from 1 to 3 mL/hour.

PRESSURE TRANSDUCER

Most pressure transducers currently used for monitoring are miniature, rugged, disposable devices.[3-7] Because of their miniature size, they can be patient mounted. All currently available disposable pressure transducers are resistive devices that convert the movement of their sensing diaphragm into an electrical signal.[8] Standards for blood pressure transducers have been developed by the Association for the Advancement of Medical Instrumentation (AAMI) and adopted by the American National Standards Institute (ANSI).[3-5] Because of such standardization, transducers from different vendors can be used interchangeably with any modern monitor.[9] In fact, errors of less than ±3% typically result from the use of such transducers *without* calibration.[9,10]

AMPLIFIER SYSTEM

Output voltage from the transducer required to drive an oscilloscope or strip recorder is furnished by an amplifier system inserted between the transducer and display. Transducer excitation is provided either from a direct current or alternating current source, with voltages ranging from of from 4 to 8 V. Most amplifier systems include low-pass filters that filter out unwanted high-frequency signals. Pressure amplifier frequency response should be "flat"—from 0 to 50 Hz—to avoid pressure waveform distortion.[1,2]

OSCILLOSCOPE DISPLAY

Pressure waveforms are best visualized on a calibrated oscilloscope.

PROCESSOR/DIGITAL DISPLAY

Digital displays provide a simple method for presenting quantitative data from the pressure waveform. They are found on most modern pressure monitoring equipment. Systolic, diastolic, and mean pressure are derived from the pressure waveforms.

RECORDER

Strip chart recorders often are used to document dynamic response characteristics, respiratory variations in PA pressures, and aberrant rhythms and pressure waveforms.

EQUIPMENT SETUP

ZEROING THE TRANSDUCER

The accuracy of blood pressure requires the establishment of an accurate reference point from which all measurements are made. The patient's midaxillary line (right heart level) is the reference point most commonly used. The "zeroing" process is used to compensate for offset caused by hydrostatic pressure differences or offset in the pressure transducer, amplifier, oscilloscope, recorder, or digital displays. Zeroing is accomplished by opening an appropriate stopcock to atmosphere and aligning the resulting air–fluid interface with the midaxillary reference point.[1,2,11] Figure 56-2 shows two methods that can be used to zero the transducer.[1,2]

Once the system is zeroed, the appropriate stopcock can be switched to allow the patient's waveform to be displayed. Because PA and PAOP are especially susceptible to improper zeroing, the zero should be verified with each measurement. Although disposable transducers have stable zero characteristics,[7,12] it is wise to zero transducers before each right heart measurement and reestablish the zero at least once per day for arterial pressures.

CALIBRATION

The sensitivity of the AAMI/ANSI disposable blood pressure transducer is fixed at 5.0 μV/V/mm Hg and calibrated by the manufacturers to within ±3%.[5] When using transducers that meet the AAMI/ANSI standard and modern monitors that interconnect with standardized transducers, there is no need to "calibrate" the transducer or monitoring system.[9] Based on current data, fixed calibration pressure monitoring systems should be purchased and maintained and fixed calibration disposable pressure transducers should be used.

If pressure transducer or monitor calibration errors are suspected in the clinical situation, the following steps are recommended: the pressure transducer should be replaced and "tested" in the laboratory situation; if the monitor module is suspect, it should be tested with a high-accuracy pressure transducer "simulator" and, if faulty, replaced and repaired.

CHECKING AND OPTIMIZING DYNAMIC RESPONSE CHARACTERISTICS

Catheter–tubing–transducer plumbing setups used in the ICU are underdamped second-order dynamic systems.[1,2,13–15] Characteristics of second-order systems are described mathematically by a second-order differential equation with characteristics determined by three mechanical parameters: elasticity, mass, and friction. These same parameters apply to a catheter–tubing–transducer system where the natural frequency (Fn in Hz) and damping coefficient zeta (ζ) determine the dynamic characteristics of the plumbing system.

Dynamic response characteristics of catheter–tubing–transducer systems are expressed by two interrelated techniques. One specifies a bandwidth (frequency) and requires that the system's frequency response be flat up to a given frequency so that a specified number of harmonics—usually 10—of the original pulse wave can be reproduced without distortion (Fig. 56-3). The second specifies the Fn and ζ.[13] The resulting plot of Fn and ζ is shown in Figure 56-4.[13] If the characteristics of the plumbing system fall in the adequate or optimal area of the graph, the pressure waveforms will be adequately reproduced. If this point falls in any of the remaining three areas, there will be pressure waveform distortion.

Catheter–tubing–transducer plumbing systems assembled under optimal conditions are usually underdamped, although a few fall into the unacceptable area. Methods

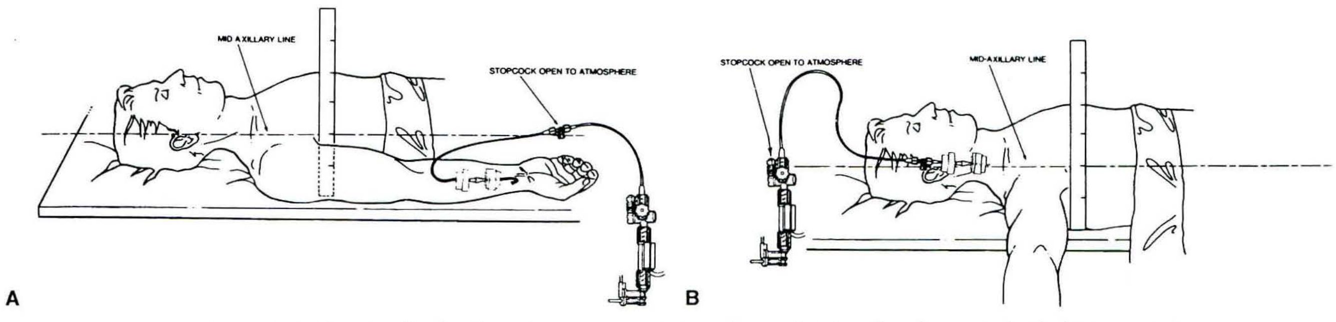

FIGURE 56-2. Two methods of zeroing a pressure transducer. Notice the place at which the water–air interface occurs should always be at the mid-axillary line when zeroing. (**A**) The stopcock near the catheter is placed at the mid-axillary line. (**B**) The stopcock is placed near the transducer at the mid-axillary line. (Adapted from Gardner RM, Hollingsworth KW: Optimizing ECG and pressure monitoring. *Crit Care Med* 1986;14:651.)

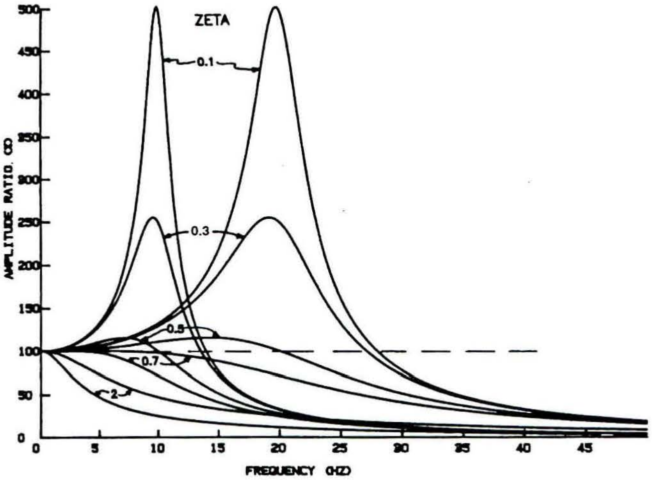

FIGURE 56-3. Family of frequency versus amplitude ratio plots for five different damping coefficients (zeta, ζ) and two different natural frequencies of 10 and 20 Hz. A damping coefficient of 0.1 occurs if the system is very underdamped, whereas a damping coefficient of 2.0 occurs when a system is overdamped. The ideal or "flat" frequency versus amplitude response is shown (*dashed line*). Notice that the response of the system with a 10-Hz natural frequency can be brought closer to the ideal "flat" response if the damping coefficient is between 0.5 and 0.7. However, by increasing the natural frequency to 20 Hz, the range of damping coefficients can be widened still further and gives nearly the same "flat" frequency response.

for optimizing the plumbing system components have been outlined.[1,13–15] In the clinical setting, there are dramatic differences between each monitoring system setup; therefore, it is mandatory to test the adequacy of each pressure monitoring system. This can be done easily using the fast-flush technique. A fast-flush is produced by opening the valve of the continuous flush device (e.g., by quickly releasing the fast-flush valve on the continuous flush system). The rapid closure generates a square wave from which the Fn and ζ of the plumbing system can be measured.

Once the fast-flush test has been executed two or three times, the dynamic response characteristics (Fn and Z) can be quickly and easily determined.[1,13] Fn can be estimated by measuring the period of each full oscillation on a strip chart recorder (Fig. 56-5*A*) after a fast-flush, and calculating the frequency from the period. To determine the ζ, any two successive peak amplitudes are measured and an amplitude ratio obtained by dividing the measured height of the lower peak by that of the amplitude of the larger peak (see Fig. 56-5*B*). This ratio is then converted to the ζ.

Once the Fn and the ζ have been determined, the data can be plotted on the graph in Figure 56-4 to ascertain the adequacy of dynamic response. Some bedside monitors and recorders may compromise the fast-flush technique with their built-in low-pass filters. These filters should be expanded to at least 50 Hz.

Several factors lead to poor dynamic responses: air bubbles in the system, usually caused by a poor initial fluid filling of the plumbing system; pressure tubing that is too long, too elastic, or has a diameter that is too small; and pressure transducers that are too elastic. The best way to enhance the system's dynamics is to maximize its Fn.

CLINICAL VERSUS LABORATORY MEASUREMENT OF DYNAMIC RESPONSE

Several investigators have studied the dynamic response characteristics of catheter–transducer systems.[1,2,13–17] Some investigators have evaluated the dynamics of pressure monitoring systems by evaluating only one element in the system. However, recent studies have examined the *complete* pressure monitoring plumbing system.[15,17]

The results of these studies show that the simpler the mechanical plumbing setup of a pressure monitoring system, the higher its fidelity.[17] The more complex the plumbing

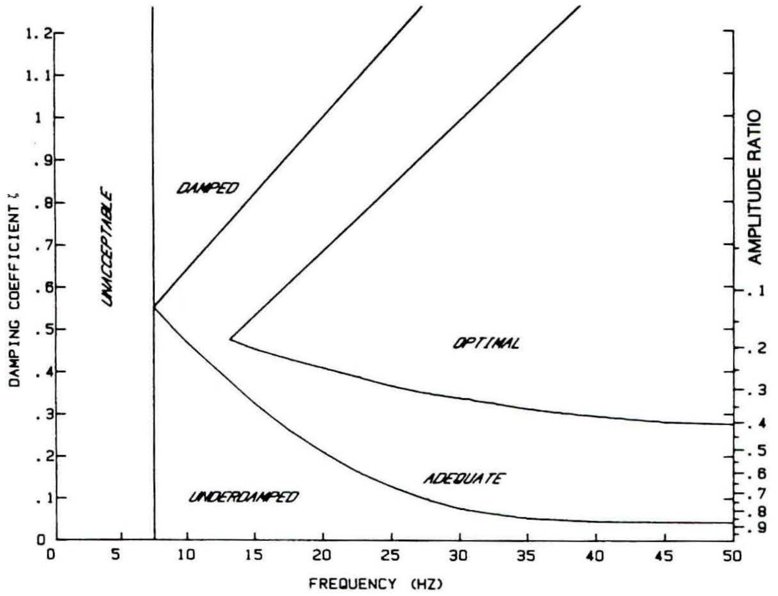

FIGURE 56-4. Plot shows the range of damping coefficient (ζ) and natural frequencies outlining the regions that indicate the type distortion of the pressure wave (see Fig. 56-5 for examples).

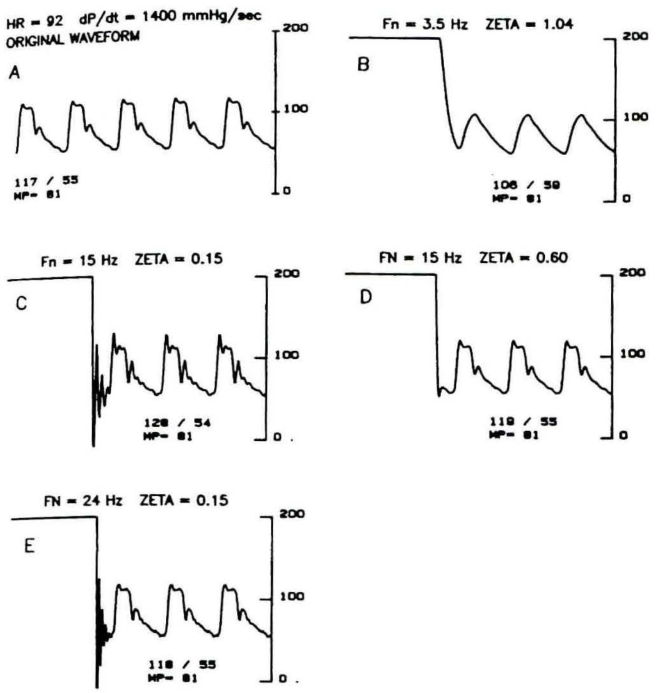

FIGURE 56-5. Arterial pressure waveforms recorded with different pressure monitoring systems. Patient heart rate is 92 with a maximum rate of change of pressure with time (dP/dt) of 1400 mm Hg/second. (**A**) The original patient waveform is shown as it might be recorded with a catheter-tipped pressure transducer. The systolic pressure is 118 mm Hg; diastolic, 55 mm Hg; and mean pressure, 81 mm Hg. (**B**) The same patient's arterial pressure waveform recorded with an "overdamped" plumbing system. ζ is 1.04 and natural frequency (Fn) is 3.5 Hz. Notice the "fast-flush" signal (*upper left*) returns slowly to the patient waveform. Systolic pressure is underestimated at 106 mm Hg, diastolic pressure is overestimated at 59 mm Hg, but mean pressure is unchanged at 81 mm Hg. (**C**) An "underdamped" condition is shown with a low damping coefficient of 0.15 and a natural frequency of 15 Hz. After the fast-flush, the pressure waveform oscillates rapidly and returns to the original waveform shape quickly. Systolic pressure is overestimated at 128 mm Hg, diastolic is nearly the same as the original at 54 mm Hg, and the mean pressure is unchanged at 81 mm Hg. (**D**) Same as in *C*, but a damping device has been inserted and adjusted.[1] The waveform is optimally damped with a damping coefficient of 0.60 and a natural frequency of 15 Hz. (**E**) An "underdamped" condition is shown but with high natural frequency of 24 Hz. Notice the pressure waveform is only slightly distorted and that the pressures are close to the true pressures.

system, that is, the greater the number of components within the system, the greater the susceptibility of that system to have degraded dynamic performance. Lack of tubing or shorter lengths of tubing minimize the chances of air bubble entrapment. Chances for setup error also were minimized with simpler plumbing systems.

The dynamic response characteristics of a system that uses catheters or elastic tubing or systems with air bubbles in them are known to have large volume displacement (Vd). Systems that use long, narrow catheters (such as the PA catheter) or have long lengths of small-diameter pressure tubing are not desirable because Fn decreases and ζ increases. Conversely, if the catheters and tubing are nonelastic and short, with large diameters and no air bubbles, then the Fn increases and ζ decreases.

Figure 56-6 illustrates the effects of tubing length and air bubbles entrapped in the system. As the Vd increases, Fn decreases and ζ increases. The magnitude of the change is multiplied for systems with long catheters or tubing (PA catheter and radial catheter with 183-cm [72-inch] tubing). For the short radial arterial catheter, the effect of tubing length is also apparent. Increasing the tubing from 30 to

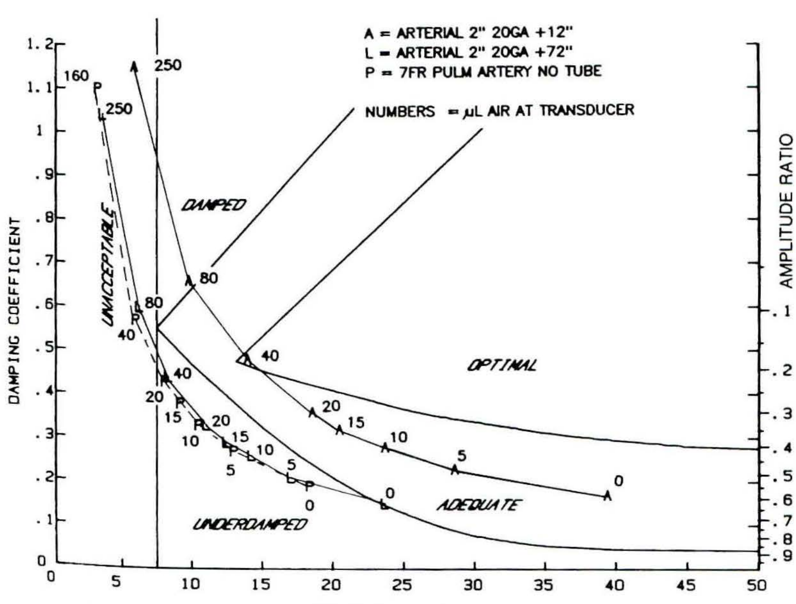

FIGURE 56-6. Plot of natural frequency versus damping coefficient for one pulmonary artery and two arterial monitoring systems showing the effect of inserting small bubbles into the transducer dome. The volumes (Vd) of air inserted in microliters are shown near the marks on the curves. The curves were generated using the modeling techniques of Taylor and coworkers. Results are presented for short radial catheters (Deseret 5cm [2 in]) with 30 cm (12 in) (index A) and 183 cm (72 in) (index L) of pressure tubing. The results from a pulmonary artery catheter system without extension tubing are shown as index P. For all situations, the operating point moves upward and to the left with the addition of air into the system. The best condition is always when *no* air is in the system.

183 cm (12 to 72 inches) with no air bubbles in the system reduces the Fn from 39 to 23 Hz. For a PA catheter system without pressure tubing, the effect of increasing air bubble size (Vd) on the system is shown. In every case, the operating point moves upward and to the left. Despite what is taught in some centers, adding air to the transducer to "damp" the pressure waveform is *not* a good idea.

The use of extension tubing for PA lines was found to be especially detrimental to the system's response. The adverse effects of long tubing are compounded because of the long length of the PA catheter. The use of extension tubing, which affords greater freedom of mobility from the transducer to the catheter, seems to be contraindicated.

This same study found that each clinical catheter–tubing–transducer system must have its dynamic response verified at frequent intervals.[17] There can be vast differences in fidelity of systems between the ideal laboratory setting and the clinical setting where the system is subject to changes over time, human assembly error, repeated blood sample withdrawal, and air entrapment. The fast-flush method of determining the dynamic response characteristics is a simple, rapid, and safe testing modality that can be easily incorporated clinically.[1,2,13,15] By performing the fast-flush testing on each clinical system, one can verify the adequacy of dynamic response and optimize it if necessary. If the fast-flush testing produces dynamic response characteristics that are inadequate, the user can take the opportunity to troubleshoot the system (i.e., remove excessive tubing length or purge air bubbles until acceptable dynamic characteristics are obtained).

SELECTING BLOOD PRESSURE TRANSDUCERS

The objective of the recently published AAMI/ANSI blood pressure transducer standards was to provide labeling and performance requirements, testing methods, and terminology to ensure that health care professionals are supplied with safe, accurate, disposable blood pressure transducers that can be used interchangeably with any monitor.[5,7,9] Fortunately, all of the current disposable transducers meet these new standards.

COMPLICATIONS OF INVASIVE PRESSURE MONITORING

The three most important risks associated with vascular cannulation and direct blood pressure monitoring are air embolism, thrombosis, and infection.

AIR EMBOLISM

Air embolism is the introduction of air into the circulatory system. Air insufflation can occur in a variety of ways into either the venous or arterial portion of the circulation. Venous air embolism may reduce or stop the flow of blood through the heart or may cause neurologic complications. The exact amount of venous air that is fatal to adults is unknown but is estimated to be between 300 and 1600 mL.[18] The rate of air injection into the venous circulation is of primary importance. Death appears to be caused by the right ventricle compressing air rather than pumping blood.

The complication from arterial air embolism is different. Air entering the left side of the heart passes quickly into the aorta. Then, depending on the position of the patient, the air may flow into the coronary arteries, cerebral arteries, or both.[18] Air entering these vessels then obstructs the blood flow to areas supplied by these vessels. In dogs, small amounts of air—between 0.05 and 1.0 mL—injected into the coronary circulation have been fatal.[18] Air embolism is best prevented by using continuous flush systems and keeping the plumbing systems closed.[18–20]

THROMBOSIS

Thrombosis can be caused by an invasive catheters, yet is an infrequent complication of arterial or PA catheterization. Embolization of clots formed on a catheter can be flushed retrograde into the central circulation from radial arterial cannulation sites. To minimize thrombus formation, continuous flush systems have been developed to keep catheters patent and prevent the need to use syringes to flush catheters.[19,21] PA catheters have had heparin bonding added to their surface to minimize thrombus formation.[22] There has been considerable discussion about the use of heparin in the flush solution and its effects on minimizing clot formation in the catheter tip.[23,24] Reports conflict regarding the need to heparinize the flush solution.[23,24] In my experience, over the last 4 years, heparin was not used in the flush solution for arterial catheters. Since heparin was eliminated, there has not been an increased rate of thrombus formation or loss of catheter function. If heparin is used in the flush solution, clinicians must be aware that a discard volume of 5 times the dead space of the catheter and tubing must be withdrawn to minimize effects on coagulation studies.[25]

INFECTION

Although invasive pressure monitoring provides valuable monitoring information, such systems also can result in bacteremia from contamination of catheters, stopcocks, pressure transducers, and flush solutions.[26–35] Most of the reported cases of pressure transducer–related infections were traced to "reusable" devices. Thus, use of totally disposable assemblies is recommended and monitoring systems should be manipulated as little as possible.[35]

SIGNAL AMPLIFICATION, PROCESSING, AND DISPLAY

Once the pressure signal has been transmitted to the transducer, the bedside monitor operates on that signal. Most monitors display the heart rate and systolic, diastolic, and mean pressure with a digital display. Evaluation of bedside monitors has found that applying the same pressure waveforms to each of three monitors gave different results.[36] In addition, it was found that none of the monitors recognized and rejected the following artifact conditions: (1) zeroing the transducer, (2) fast-flushing the system, and (3) drawing blood from the patient. These conditions occur several times daily during normal patient care and result in false alarms and erroneous trend data logging.[37]

To eliminate these problems, new algorithms are being developed for bedside pressure monitors. Preliminary testing has shown that these enhanced algorithms produce dramatic improvements in the bedside monitor's ability to evaluate pressure waveforms in the clinical setting.[38]

REFERENCES

1. Gardner RM, Hollingsworth KW: Optimizing ECG and pressure monitoring. *Crit Care Med* 1986;14:651
2. Gardner RM: Hemodynamic monitoring: from catheter to display. *Acute Care* 1986;12:3
3. Gardner RM, Kutik M: *American National Standard for Blood Pressure Transducers: General.* Arlington, VA, Association for the Advancement of Medical Instrumentation (AAMI), and American National Standards Institute (ANSI), 1986
4. Gardner RM, Kutik M: *American National Standard for Interchageability and Performance of Resistive Bridge Type Blood Pressure Transducers.* Arlington, VA, Association for the Advancement of Medical Instrumentation (AAMI), and American National Standards Institute (ANSI), 1986
5. Cooper T, Paulsen AW: *American National Standard for Blood Pressure Transducers.* Arlington, VA, Association for the Advancement of Medical Instrumentation (AAMI), and American National Standards Institute (ANSI), 1994
6. Disposable pressure transducers. *Health Devices* 1984;13:268
7. Disposable pressure transducers: evaluation. *Health Devices* 1988;17:75
8. Gardner RM, Hujcs M: Fundamentals of physiologic monitoring. In: Susan G. Osguthorpe (ed). *Concepts of Physiological Monitoring/Hemodynamic Pressure Monitoring Systems: Physiological Monitoring. AACN Clinical Issues in Critical Care Nursing.* Philadelphia, JB Lippincott, 1993:11
9. Gardner RM: Accuracy and reliability of disposable pressure transducers coupled with modern pressure monitors. *Crit Care Med* 1996 (May, in press)
10. Bailey RH, Bauer JH, Yanos J: Accuracy of disposable pressure transducers used in the critical care setting. *Crit Care Med* 1995;23:187
11. Geddes LA: The significance of a reference in the direct measurement of blood pressure. *Med Instrum* 1986;20:331
12. Ahrens T: How often is it necessary to zero-balance a disposable transducer used for intravascular and intracardiac pressure readings? *Crit Care Nurse* 1994;14:98
13. Gardner RM: Direct blood pressure measurement: dynamic response requirements. *Anesthesiology* 1981;54:227
14. Kleinman B: Understanding natural frequency and damping and how they relate to the measurement of blood pressure. *J Clin Monit* 1989;5:137
15. Kleinman B, Powell S, Kumar P, et al: The fast flush does measure the dynamic response of the entire blood pressure monitoring system. *Anesthesiology* 1992;77:1215
16. Taylor BC, Ellis DM, Drew JM: Quantification and simulation of fluid-filled catheter/transducers systems. *Med Instrum* 1986;20:123
17. Gibbs NC, Gardner RM: Dynamics of invasive pressure monitoring systems: clinical and laboratory evaluation. *Heart Lung* 1988;17:43
18. Toll MO: Direct blood-pressure measurements: risks, technology evolution and some current problems. *Med Biol Eng Comput* 1984;22:2
19. Gardner RM, Bond EL, Clark JS: Safety and efficacy of continuous flush systems for arterial and pulmonary artery catheters. *Ann Thorac Surg* 1977;23:534
20. Disposable blood pressure transducers: calibration methods. *Health Devices* 1993;22:97
21. Gardner RM, Warner HR, Toronto AF, et al: Catheter flush system for continuous monitoring of central arterial pulse waveform. *J Appl Physiol* 1970;29:911
22. Hoar PF, Wilson RM, Mangano DT, et al: Heparin bonding reduces thrombogenicity of pulmonary-artery catheters. *N Engl J Med* 1981;305:993
23. Hook ML, Reuling J, Luettgen ML, et al: Comparison of patency of arterial lines maintained with heparinized and non-heparinized infusions. *Heart Lung* 1987;16:693
24. Clifton GD, Branson P, Kelly HJ, et al: Comparison of normal saline and heparin solution for maintenance of arterial catheter patency. *Heart Lung* 1991;20:115
25. Reihnardt ACR, Tonneson AS, Goodnough SKC: Minimum discard volume from arterial catheters to obtain coagulation studies free of heparin effect. *Heart Lung* 1987;16:699
26. Weinstein RA, Stam WE, Kramer L, et al: Pressure monitoring devices: overlooked source of nosocomial infection. *JAMA* 1976;236:936
27. Hekker TA, van Overhagen W, Schneider AJ: Pressure transducers: an overlooked source of sepsis in the intensive care unit. *Intensive Care Med* 1990;16:511
28. Thomas F, Burke JP, Parker J, et al: The risk of infection related to radial vs. femoral sites for arterial catheterization.*Crit Care Med* 1983;11:807
29. Sommers MS, Baas LS: Nosocomial infections related to four methods of hemodynamic monitoring. *Heart Lung* 1987;16:13
30. Simmons BP: Centers for Disease Control: guidelines for prevention of infections related to intravascular pressure-monitoring systems. *Infect Control* 1982;3:68
31. Luskin RL, Weinstein RA, Nathan C, et al: Extended use of disposable pressure transducers: a bacteriologic evaluation. *JAMA* 1986;255:916
32. Maki DG, Botticelli JT, LeRoy ML, et al: Prospective study of replacing administration sets for intravenous therapy at 48 vs 72 hour intervals: 72 hours is safe and cost effective. *JAMA* 1987;258:1777
33. O'Malley MK, Rhame FS, Cerra FB, et al: Value of routine pressure monitoring system changes after 72 hours of continuous use. *Crit Care Med* 1994;22:1424
34. Mermel LA, Maki DG: Epidemic bloodstream infections from hemodynamic pressure monitoring: signs of the times. *Infect Control Hosp Epidemiol* 1989;10:47
35. Mermel LA, Maki DG: Infectious complications of Swan-Ganz pulmonary-artery catheters: pathogenesis, epidemiology, prevention, and management. State of the art. *Am J Resp Crit Care Med* 1994;149:1020
36. Maloy L, Gardner RM: Monitoring systemic arterial blood pressure: strip recording versus digital display. *Heart Lung* 1986;15:627
37. Gardner RM, Monis SM, Oehler P: Monitoring direct blood pressure: algorithm enhancements. *IEEE Comput Cardiol* 1986;13:607
38. Ellis DM: Interpretation of beat-to-beat blood pressure values in the presence of ventilatory changes. *J Clin Monit* 1985;1:65